REMARKS

Claims 1-20 are pending in this application.

Claims 1-20 have been rejected.

Claims 1-5, 9-13, 15 and 18-20 have been amended as shown above.

Claims 1-20, as amended, are now pending in this application.

Reconsideration of Claims 1-20, as amended, is respectfully requested.

I. AMENDMENT TO THE SPECIFICATION

The equation on Page 14, Line 22 has been amended to correct typographical errors. The context of the specification makes it clear that no new matter has been added by this amendment.

II. REJECTIONS UNDER 35 U.S.C. § 112

The March 13, 2007 Office Action rejected Claims 1-20 under 35 U.S.C. 1 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. In particular, the Office Action stated "Claims 1, 9, and 15 recite 'a factor specific to mounting of the light source' which is not clear what applicant intends to claim." (March 13, 2007 Office Action, Page 2, Lines 12-13).

In response, the Applicant has amended the claims to clarify that the "factor specific to mounting of the light source" is a conversion factor θ_{ja} that is specific to a manner in which the

The forward current I_f, which for most VCSELs ~~has~~ have a small and predictable variation dependent on forward voltage/temperature, may be measured using a series resistance, calculated, or determined. Similarly, the temperature T(VCSEL) may be calculated or determined from a lookup table based on the forward voltage.

[0021] Accordingly, in one embodiment of the present invention illustrated by process 2~~3~~00, whenever an output power measurement is initiated (step ~~3~~201), the forward voltage V_f of the VCSEL and ambient temperature T(ambient) around the VCSEL are measured (step 2~~3~~02). The forward current I_f and die temperature T(VCSEL) are determined from the measured forward voltage (step ~~3~~203), either by calculation or using a look-up as described above. The optical power is then calculated (step ~~3~~204), and the process becomes idle until another power measurement is required (step 2~~3~~05).

[0022] The embodiment of FIGURE ~~3A~~ 2 avoids the need for a complex lens to reflect part of the transmitted light onto a monitor diode used to control the average power of the transmitted light, reducing mechanical and optical design complexity, assembly process complexity, and cost. Potentially more accurate power information is available,

light source is mounted. (Specification, Page 14, Lines 15-19). As shown in the equation on Page 14, Line 11 and in the equation on Page 14, Line 22, dividing by the conversion factor θ_{ja} converts a value of temperature to a value of power. The Applicant respectfully submits that the claims, as amended, are now not indefinite in view of the specification. The Applicant respectfully requests that the indefiniteness rejections be withdrawn.

III. REJECTIONS UNDER 35 U.S.C. § 103

The March 13, 2007 Office Action rejected Claims 1-4, 6-7, 9-12, 14-15 and 17-18 under 35 U.S.C. § 103(a) as being obvious in view of U.S. Patent No.6,853,657 to Althaus et al. ("*Althaus*"). The March 13, 2007 Office Action also rejected Claims 1, 5-6, 7-11 and 13-20 under 35 U.S.C. § 103(a) as being obvious in view of U.S. Patent No. 6,356,774 to Bernstein et al. ("*Bernstein*").

In response, the Applicant has amended Claims 1-5, 9-13, 15 and 18-20.

In *ex parte* examination of patent applications, the Patent Office bears the burden of establishing a *prima facie* case of obviousness. MPEP § 2142, p. 2100-125 (8th ed., rev. 5, August 2006). Absent such a *prima facie* case, the applicant is under no obligation to produce evidence of nonobviousness. *Id.*

A *prima facie* case of obviousness is established when the teachings of the prior art itself suggest the claimed subject matter to a person of ordinary skill in the art. *In re Bell*, 991 F.2d 781, 783, 26 USPQ2d 1529, 1531 (Fed. Cir. 1993). To establish a *prima facie* case of obviousness, three

basic criteria must be met. First, there must be some suggestion or motivation, either in the references themselves or in the knowledge generally available to one of ordinary skill in the art, to modify the reference or to combine reference teachings. Second, there must be a reasonable expectation of success. Finally, the prior art reference (or references when combined) must teach or suggest all the claim limitations. The teaching or suggestion to make the claimed invention and the reasonable expectation of success must both be found in the prior art, and not be based on an applicant's disclosure. MPEP § 2142.

Claim 1, Claim 9 and Claim 15, as amended, recite that the forward voltage is employed to determine a forward current through the light source and a die temperature of the light source. Such features are not found in the *Althaus* reference. The cited portions of *Althaus* read:

> It is accordingly an object of the invention to provide a method and a device for simply and precisely determining the output power of a semiconductor laser diode, which overcome the above-mentioned disadvantages of the prior art apparatus and methods of this general type, and which do not require a monitor diode.
>
> With the foregoing and other objects in view there is provided, in accordance with the invention, a method for determining an output power of a semiconductor laser diode being operated with a diode current. The method includes steps of: conducting a defined measuring current through the semiconductor laser diode in a forward direction, the measuring current being smaller than a threshold current of the semiconductor laser diode; measuring a forward voltage being dropped across the semiconductor laser diode as a result of the measuring current; and using at least one calibration curve to determine the output power of the semiconductor laser diode from the forward voltage that was measured.
>
> With the foregoing and other objects in view there is also provided, in accordance with the invention, a measuring device for determining an output power of a semiconductor laser diode being operated with a diode current. The measuring device includes: a device for generating a defined constant measuring current; a device for detecting the forward voltage being dropped across the semiconductor laser diode when the defined measuring current is conducted in the forward direction through the semiconductor laser diode; and a device for determining the output

> power of the semiconductor laser diode from the forward voltage that is measured and at least one calibration curve.
>
> . . . .
>
> The measuring device for determining the output power of a semiconductor laser diode that is operated with a diode current has the following elements: a) a device for generating a defined, constant measuring current, b) a device for detecting a forward voltage that drops across a semiconductor laser diode through which the defined measuring current is conducted in the forward direction, and c) a device which determines the output power of the semiconductor laser diode from the measured forward voltage by using at least one calibration curve that is preferably specific to the diode current. The measuring device in this case executes the method explained above.

(*Althaus*, column 2, lines 22–52, column 4, lines 38–49). Thus *Althaus* specifically teaches using a defined, constant measuring current and measuring the forward voltage drop across the laser diode to determine output power using a calibration curve. *Althaus* does not teach using the measured forward voltage drop to determine forward current as required by the claims.

The Applicant previously stated that Ohm's Law (V=IR) is only applicable to ohmic devices. Diodes (or, in the instant case, laser diodes) are not ohmic devices. The current-voltage relationship for pn junction diodes is not linear. The *Althaus* reference actually teaches that the current-voltage relationship for a laser diode is non-ohmic, since a defined measurement current is passed through the diode and the forward voltage drop measured. If current and voltage were related by Ohm's Law as asserted in the Office Action, measurement of the forward voltage drop would be unnecessary.

More to the point, regardless of whether one <u>could</u> (in theory) derive the current through a laser diode from the measured forward voltage drop, *Althaus* does not <u>teach</u> employing the measured forward voltage drop to determine forward current as required by the claims.

The Examiner stated (1) that Ohm's Law is appropriate to determine the forward current based on the measured forward voltage at a certain value of the forward voltage, and (2) that the relationship between current and voltage of the laser diode is not totally nonlinear at all ranges of forward voltage or all ranges of forward current. (March 13, 2007 Office Action, Page 3, Lines 15-18). The Examiner further stated that "Therefore it would have been obvious to the one having ordinary skill in the art at the time the invention was made to used the measured forward voltage to determine the forward current based on Ohm's Law for at least a certain forward voltage range or from a look-up table (col. 3, line 10-19)." (March 13, 2007 Office Action, Page 3, Lines 18-21). The Applicant respectfully traverses this assertion of the Examiner for the following reasons.

The *Althaus* reference does not disclose the values of forward voltage for which Ohm's Law is applicable. While Ohm's Law may apply to a certain value of the forward voltage, the *Althaus* reference does not disclose this value (or even a range of values) for which Ohm's Law is applicable. If Ohm's Law were applicable, then the *Althaus* method would not have to use an iteration method (shown in Figure 2 of *Althaus*) to find the output power. (*Althaus*, Column 6, Lines 27-32). The iteration method is required because a laser diode is a non-linear device.

With respect to the element of using the forward voltage to determine a die temperature of the light source, such a feature is not found in the *Althaus* reference. The cited portion of the *Althaus* reference reads:

> The method proposes a novel approach in measuring the output power of a semiconductor laser diode, since the determination of the output power is performed not via additional measuring elements, but via the physical semiconductor property of the temperature dependence of the forward voltage of the semiconductor laser diode. In this case, use is made of the physical effect that the forward voltage of a semiconductor laser diode varies with the temperature of the laser-active region of the semiconductor laser diode when the semiconductor laser diode is operated with a constant measuring current that flows in the forward direction and that is below the threshold current. The output power of the semiconductor laser diode likewise varies with temperature.
>
> The exact temperature dependence of the forward voltage and thus also the functional dependence of the forward voltage on the respective output power is determined for a semiconductor laser diode, individually by using calibration curves that are recorded. There is a need to record a specific calibration curve in each case for a multiplicity of different diode currents. This family of the calibration curves required for using the semiconductor laser diode is preferably already determined by the module manufacturer and is stored in a storage device of the module.
>
> . . . .
>
> Using the data from the family of characteristic curves which represent the relationship between the forward voltage and the output power of the semiconductor laser diode for a multiplicity of different diode currents, the output power of the laser-active region of the semiconductor laser diode can be determined precisely at any time solely by measuring the forward voltage.

(*Althaus*, column 2, line 63 through column 3, line 19, column 3, lines 24–30). Thus, while *Althaus* notes the dependence of forward voltage on temperature, *Althaus* does not teach or suggest employing the forward voltage to determine temperature. Instead, *Althaus* teaches employing the forward voltage to determine output power directly from a family of calibration curves (based on different currents) without first determining temperature. The *Althaus* method requires "a specific calibration curve in each case for a multiplicity of different diode currents" preferably already determined by the module manufacturer. (*Althaus*, Column 3, Lines 14-19).

The *Althaus* method does not take into account (1) the ambient temperature around the light source or (2) the effect on the output power due to the manner in which the light source is mounted.

Therefore, Claims 1-4, 6-7, 9-12, 14-15 and 17-18, as amended, are not obvious in view of the *Althaus* reference.

The March 13, 2007 Office Action also rejected Claims 1, 5-6, 7-11 and 13-20 under 35 U.S.C. § 103(a) as being obvious in view of U.S. Patent No. 6,356,774 to Bernstein et al. ("*Bernstein*"). The Applicants respectfully submit that Claims 1, 5-6, 7-11 and 13-20, as amended, are not obvious in view of the *Bernstein* reference.

The Examiner stated that the *Bernstein* reference disclosed the Applicant's invention as claimed in Claims 1, 9-11 and 14-15 except that the *Bernstein* reference did not explicitly disclose the element of determining a forward current though the light source based on the measured forward voltage. (March 13, 2007 Office Action, Page 4, Lines 12- 19). The Examiner also stated that it would have been obvious to one having ordinary skill in the art at the time the invention was made to use the measured values of forward voltage to determine the forward current based on Ohm's Law for at least a certain forward voltage range or form a look-up table. (March 13, 2007 Office Action, Page 4, Line 19 to Page 5, Line 2). The Applicant respectfully traverses these assertions of the Examiner for the reasons set forth below.

The Applicant repeats and incorporates by reference the Applicant's previous remarks and arguments made in connection with the obviousness rejections made with the *Althaus* reference. The *Bernstein* reference discloses an oximeter sensor circuit. The *Bernstein* device does not

determine an output power for the emitted light. Therefore, the *Bernstein* device does not need to determine a forward current through the light source based on the measured forward voltage. Therefore, there is no motivation to modify the disclosure of the Bernstein device to determine the forward current based on Ohm's Law. Furthermore, the *Bernstein* reference does not disclose the values of forward voltage for which Ohm's Law is applicable. While Ohm's Law may apply to a certain value of the forward voltage, the *Bernstein* reference does not disclose this value (or even a range of values) for which Ohm's Law is applicable to a nonlinear laser diode.

The *Bernstein* method does not take into account (1) the difference between the die temperature and the ambient temperature around the light source or (2) the effect on the output power due to the manner in which the light source is mounted.

The Examiner also stated that "Therefore it is believed that the sensor 58 is coupled to the controller 64 for providing the ambient temperature to the controller." (March 13, 2007 Office Action, Page 5, Lines 16-17). The Applicant respectfully traverses this assertion of the Examiner. Sensor 58 is "an optional resistor 58 for identifying the sensor type." (*Bernstein*, Column 11, Lines 15-16, Figure 3). It is clear that the sensor 58 is not a temperature sensor.

The Examiner also stated that with respect to Claims 7-8, "It would have been obvious to the one having ordinary skill in the art at the time the invention was made to provide a processor and a network connection through the optical subassembly to the optical transmission medium transmit light and control the light source." (March 13, 2007 Office Action, Page 5, Lines 9-12). The Applicant respectfully traverses this assertion of the Examiner. There is nothing in the

Bernstein reference that refers to a network connection or to the transmission of data over an optical transmission medium. This concept comes from the Applicant's disclosure.

Therefore, Claims 1, 5-6, 7-11 and 13-20, as amended, are not obvious in view of the *Bernstein* reference.

IV. CONCLUSION

As a result of the foregoing, the Applicant asserts that the claims in the patent application are in condition for allowance and respectfully requests that this patent application be passed to issue. The Applicant denies any statement, position or averment of the Examiner that is not specifically addressed by the foregoing argument and response. The Applicant reserves the right to submit further arguments in support of his above stated position as well as the right to introduce relevant secondary considerations including long-felt but unresolved needs in the industry, failed attempts by others to invent the invention, and the like, should that become necessary.

SUMMARY

If any issues arise, or if the Examiner has any suggestions for expediting allowance of this Application, the Applicant respectfully invites the Examiner to contact the undersigned at the telephone number indicated below or at *wmunck@munckbutrus.com.*

The Commissioner is hereby authorized to charge any fees connected with this communication or credit any overpayment to Deposit Account No. 50-0208.

Respectfully submitted,

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DOCKET NO. P05746 (NATI15-05746) PATENT

METHOD OF SENSING VCSEL LIGHT OUTPUT POWER BY MONITORING ELECTRICAL CHARACTERISTICS OF THE VCSEL

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METHOD OF SENSING VCSEL LIGHT OUTPUT POWER BY MONITORING ELECTRICAL CHARACTERISTICS OF THE VCSEL

TECHNICAL FIELD OF THE INVENTION

[0001] The present invention is directed, in general, to control of data transmission optical sources and, more specifically, to power control over optical sources without use of a monitor diode.

BACKGROUND OF THE INVENTION

[0002] Data transmission over an optical medium such as an optical fiber typically requires use of a laser classified by the limit imposed on output power (and the corresponding danger associated with use of such output power), with many systems employing, for instance, a Class 2 laser. Accordingly, the output power of lasers employed must satisfy stringent eye safety requirements and equally stringent requirements defined by the transmission protocol (e.g., Ethernet, fiber channel, etc.).

[0003] Conventional optical power control schemes employ a p-type/intrinsic/n-type (PIN) semiconductor light detection monitor diode and a partially reflective lens to

monitor the output of a vertical cavity surface emitting laser (VCSEL) or other light source. A small fraction of the light emitted by the laser is reflected to the PIN diode, which converts the light to an electrical current sensed by a transimpedance amplifier for conversion into a voltage. The voltage representative of the reflected light is compared against a reference voltage and an error signal generated on the basis of that comparison is employed to servo the VCSEL light output power to desired level.

[0004] Use of a complex lens to partially reflect transmitted light onto a monitor diode employed to control output power introduces mechanical and optical design complexities and assembly complexity, and increases costs. In addition, detailed knowledge of the package design and/or VCSEL characteristics is typically required.

[0005] There is, therefore, a need in the art for a system and technique for monitoring output power from a data transmission light source without requiring use of a monitor diode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, wherein like numbers designate like objects, and in which:

[0007] FIGURE 1 depicts a computer implementing prediction and control of optical modulation amplitude and/or extinction ratio for an optical sub-assembly therein according to one embodiment of the present invention; and

~~[0008] FIGURE 2 is a high level flowchart illustrating a process of controlling optical modulation amplitude and/or extinction ratio for an optical sub-assembly according to one embodiment of the present invention;~~

[0008] FIGURE ~~3A~~ 2 is a high level flowchart illustrating a process for determining average power without utilizing feedback from an optical monitor according to one embodiment of the present invention~~;~~.

~~[0010] FIGURE 3B depicts a low bandwidth diode optical monitor configuration for determining average output power according to another embodiment of the present invention; and~~

~~[0011] FIGURE 4A through 4E illustrate simulation results for operation of a low-bandwidth diode optical monitor configuration for determining average output power according to one embodiment of the present invention.~~

DETAILED DESCRIPTION OF THE INVENTION

[0009] To address the above-discussed deficiencies of the prior art, it is a primary object of the present invention to provide, for use in an optical subassembly for network transmission of data over an optical fiber from a computer, determination of output power of light emitted from a data transmission light source based upon forward voltage, forward current, ambient temperature and a factor specific to the manner in which the light source is mounted. Output power is determined with sufficient accuracy to control operation of the data transmission light source for compliance with eye safety and transmission protocol requirements without use of a complex lens and monitor diode.

[0010] The foregoing has outlined rather broadly the features and technical advantages of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features and advantages of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art will appreciate that they may readily use the conception and the specific embodiment disclosed as a basis for modifying or designing

other structures for carrying out the same purposes of the present invention. Those skilled in the art will also realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

[0011] Before undertaking the detailed description below, it may be advantageous to set forth definitions of certain words or phrases used throughout this patent document: the terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation; the term "or" is inclusive, meaning and/or; the phrases "associated with" and "associated therewith," as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, or the like; and the term "controller" means any device, system or part thereof that controls at least one operation, whether such a device is implemented in hardware, firmware, software or some combination of at least two of the same. It should be noted that the functionality associated with any particular controller might be centralized or distributed, whether locally or remotely. Definitions for

certain words and phrases are provided throughout this patent document, and those of ordinary skill in the art will understand that such definitions apply in many, if not most, instances to prior as well as future uses of such defined words and phrases.

[0012] FIGURES 1 through ~~4E~~2, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the present invention may be implemented in any suitably arranged device.

[0013] FIGURE 1 depicts a computer implementing prediction and control of optical modulation amplitude and/or extinction ratio for an optical sub-assembly therein according to one embodiment of the present invention. Those skilled in the art will recognize that the full construction and operation of a mobile computer is not depicted and described. Instead, for simplicity and clarity, only so much of a mobile computer as is unique to the present invention or necessary for an understanding of the present invention is depicted or described.

[0014] Computer 100 includes a processor 101, main memory 102, and bridges 103 and 104 enabling the processor 101 to interface with other system elements. Processor 101 employs a memory controller host or "north bridge" 103 to interface with main memory 102 and graphics units (not shown). Processor 101 employs an interface controller host or "south bridge" 104, coupled to the north bridge 103 by a hub interface, to interface with other devices over standard, general-purpose buses such as a Peripheral Component Interconnect (PCI) bus.

[0015] In the present invention, south bridge 104 is coupled (using, for instance, a card mounted within a PCI bus slot) to an optical sub-assembly (OSA) 105 including an optical transceiver and a controller (not shown) providing a network connection over an optical medium, such as an Ethernet network connection over optical fiber(s). ~~Control of the o~~Optical transmission power for optical sub-assembly 105 is based on optical modulation amplitude or extinction ratio and average power in the manner described in further detail below.

[0016] In describing the scheme for control over extinction ratio according to the present invention, the following values are employed: P_o represents the instant-

aneous VCSEL output power; P_{avg} represents the time-averaged (low pass filtered) value of output power P_o; I represents VCSEL current; I_1 represents logical "1" ("on") level current and I_0 represents logical "0" ("off") level current, which typically is not zero; I_{avg} represents average VCSEL current calculated from $I_{avg}=(I_1+I_0)/2$; I_{th} represents threshold current; I_{mod} represents modulation current calculated from $I_{mod}=I_1-I_0$; η represents slope efficiency; $ER=10\log(P_1/P_0)$ represents extinction ratio; $OMA=(P_1-P_0)$ represents optical modulation amplitude, more commonly employed in current control systems than ER; and T_n denotes sampling time.

[0017] The power output of a VCSEL is given by:

$$P_o=(I-I_{th})\cdot\eta\text{, and}$$

$$P_{avg}=(I_{avg}-I_{th})\cdot\eta\,.$$

The present invention relates to prediction of average power. Other means may be employed to control extinction ratio based on average power values determined according to the present invention. ~~Assuming that two samples of average power~~ $\cancel{P_{avg}(T_1)}$ ~~and~~ $\cancel{P_{avg}(T_2)}$ ~~are taken, and further assuming that the threshold current~~ $\cancel{I_{th}}$ ~~and slope efficiency~~

~~η remain constant across those measurements, the expression above for average power may be written as:~~

$$P_{avg}(T_1) = (I_{avg}(T_1) - I_{th}) \cdot \eta \text{, and}$$

$$P_{avg}(T_2) = (I_{avg}(T_2) - I_{th}) \cdot \eta .$$

~~Solving these equations for the two desired variables:~~

$$I_{th} = \frac{P_{avg}(T_1) \cdot I_{avg}(T_2) - P_{avg}(T_2) \cdot I_{avg}(T_1)}{P_{avg}(T_1) - P_{avg}(T_2)}, \qquad (1)$$

$$\eta = \frac{P_{avg}(T_1) - P_{avg}(T_2)}{I_{avg}(T_1) - I_{avg}(T_2)}. \qquad (2)$$

~~The average power and average current will depend on the logical data value being transmitted at times T_1 and T_2.~~

~~[0021] The exemplary embodiment of the present invention utilizes equations (1) and (2) above in real time control of both the average power and extinction ratio. Since average power monitoring is being performed in real time, with the results fed back to control the bias current I_{bias} and modulation current I_{mod}, by using two appropriate samples of average power one parameter (e.g., slope efficiency) may be very closely approximated while the other parameter (threshold current in this example) is precisely known from the two measurements.~~

~~[0022] FIGURE 2 is a high level flowchart illustrating a process of controlling optical modulation amplitude and/or~~

~~extinction ratio for an optical sub-assembly according to one embodiment of the present invention. In the example depicted and described, average power is controlled by varying~~ ~~I_1~~ ~~and extinction ratio is controlled by varying~~ ~~I_{mod}~~~~. In an alternative embodiment, the dependence of optical modulation amplitude on the modulation current~~ ~~I_{mod}~~ ~~could be determined from the equations given above, and controlled in lieu of extinction ratio.~~

~~[0023] The process 200 begins by initialization of~~ ~~$I_1=I_{1,min}$, $I_{mod}=0$~~ ~~and~~ ~~$I_{th}=I_{th,min}$~~ ~~(step 201). Next, and average output power sample~~ ~~$P_{avg}(N)$~~ ~~is determined (step 202) from, for example, electrical characteristics of the VCSEL or the output signal from a low bandwidth monitor diode, as described in further detail below. The average power measurement~~ ~~$P_{avg}(N)$~~ ~~is compared to a target value~~ ~~P_{target}~~ ~~to determine if the average power measurement is less than the target (step 203). If so, the present logical 1 level current~~ ~~I_1~~ ~~(the maximum current driven through the VCSEL) is incremented (step 204), provided the maximum operating limit set for that parameter~~ ~~$I_{1,max}$~~ ~~(e.g., the maximum current that the VCSEL can tolerate) has not previously been reached. If not, however, the average power~~

~~measurement $P_{avg}(N)$ is compared to a target value P_{target} to determine if the average power measurement exceeds or is greater than the target (step 205). If so, the logical 1 level current I_1 is decremented (step 206), provided the minimum operating limit set for that parameter $I_{1,min}$ has not previously been reached.~~

~~[0024] If the average power measurement $P_{avg}(N)$ is neither less than nor greater than the target (i.e., the average power measurement $P_{avg}(N)$ equals the target value), the extinction ratio may be presumed to have been set to an acceptable value in a previous iteration of the process such that no further adjustment is required, and the process returns to step 202. Note that this may also be the case when the average power measurement $P_{avg}(N)$ does not equal the target value, but the logical 1 level current I_1 cannot be adjusted (i.e., I_1 has already reached $I_{1,max}$ or $I_{1,min}$).~~

~~[0025] On the other hand, if the logical 1 level current I_1 is incremented or decremented, the modulation current I_{mod} is altered to achieve (in this example) the desired extinction ratio (step 207). For this purpose, it may be noted that:~~

$$\cancel{ER = 10 \cdot \log_{10}\left(\frac{P_1}{P_0}\right),}$$

$$\cancel{\Rightarrow ER = 10 \cdot \log_{10}\left(\frac{I_1(N) - I_{th}(N)}{I_1(N) - I_{mod}(N) - I_{th}(N)}\right)}$$

~~so that, using the desired extinction ratio value and the threshold current estimate from the previous loop cycle, the modulation current may be set by:~~

$$\cancel{I_{mod}(N) \approx (1 - 10^{-ER/10}) \cdot (I_1(N) - I_{th}(N-1)).}$$

~~[0026] Finally, before proceeding with the next loop iteration (i.e., returning to step 202), the estimated threshold current I_{th} is calculated for use in the next iteration (step 208).~~

[0018] FIGURE ~~3A~~ 2 is a high level flowchart illustrating a process for determining average power without utilizing feedback from an optical monitor according to one embodiment of the present invention. As noted above, the VCSEL light output power may be monitored directly utilizing a lens and PIN diode. Alternatively, however, the average power measurement $P_{avg}(N)$ required for estimating and controlling optical modulation amplitude or extinction ratio as described above may be determined based on conservation of power and temperature measurements.

[0019] While a temperature sensor such as a diode, a thermocouple, or the like may be integrally formed with the VCSEL for use in measuring the die temperature, the forward voltage V_f of a VCSEL has a well-known dependence on temperature. Accordingly, the die temperature for the VCSEL may be determined by monitoring the forward voltage V_f, which is commonly already measured. The die temperature is also dependent on total power dissipated in the VCSEL and the temperature coefficient of the optical sub-assembly (OSA), such that VCSEL light power may be expressed as:

$$\text{Power(optical)} = \text{P(electrical)} - \frac{\text{T(VCSEL)} - \text{T(ambient)}}{\theta_{ja}},$$

where T(VCSEL) is a function of the VCSEL forward voltage, T(ambient) is the ambient temperature surrounding the VCSEL integrated circuit, measured by a temperature sensor, and θ_{ja} (where "ja" represents junction-to-ambient, as opposed to junction-to-case and case-to-ambient) is a value specific to the manner in which the VCSEL is mounted and may be determined for a specific design and fabrication process.

[0020] The expression above for power may be rewritten as:

$$\text{Power(optical)} = V_f(\text{VCSEL}) \cdot I_f(\text{VCSEL}) - \frac{\overset{T}{\text{fn}}(V_f(\text{VCSEL})) - \text{T(ambient)}}{\theta_{ja}}.$$

without the necessity for detailed knowledge of the packed design or VCSEL characteristics.

~~[0032] FIGURE 3B depicts a low bandwidth diode optical monitor configuration for determining average output power according to another embodiment of the present invention. As noted above, a common configuration 306 for measuring output power involves passing the light emitted by VCSEL 307 through a complex lens 308 passing most of the light through to the transmission medium (not shown) but reflecting a portion onto a monitor diode 309.~~

~~[0033] In current systems, the PIN monitor diode 309 is typically either slow and used to control average power only, causing extinction ratio and optical modulation amplitude to vary with operating conditions, or very expensive full bandwidth PIN diodes that more accurately monitor transmitted light. In the present invention, low bandwidth PIN diodes are employed to collect the power measurements required to estimate and control extinction ratio or optical modulation amplitude as described above. Such low bandwidth PIN diodes are less expensive~~

~~[0034] Accordingly, monitor diode 309 is an inexpensive PIN diode with low bandwidth, employed to extract information about light modulation including average output power measurements employed to control both average power~~

~~P_{avg} and extinction ratio or optical modulation amplitude. As long as the monitor diode has sufficient bandwidth to overlap the lower end of the transmitted spectrum (with a bandwidth of about 10% frequency of the emitted light being sufficient), the output current from the monitor diode 309 will reach the peak value for long run lengths (e.g., long runs of consecutive logical 1's). Therefore, by monitoring the peak-to-peak value of the output from monitor diode 309 using a peak detector, optical modulation amplitude may be estimated. In other words, the output eye of the monitor diode 309 will be completely closed due to intersymbol interference (ISI), but the peak-to-peak value is a true (and direct) representation of the VCSEL output optical modulation amplitude.~~

~~[0035] FIGURE 4A through 4E illustrate simulation results for operation of a low-bandwidth diode optical monitor configuration for determining average output power according to one embodiment of the present invention. FIGURE 4A depicts the equivalent circuit 400 employed for simulation, in which the signal source 401 generating 1.25 giga-bits per second (Gbps) data at various amplitudes is coupled to a low pass filter (R_0 and C_0) approximating the bandwidth of an inexpensive, low frequency PIN sensor~~

~~diode. The output of the filter is coupled by alternating current (AC) coupling capacitor C_2 to peak detectors 402-403 detecting upper and lower signal peaks for the output of the low pass filter.~~

~~[0036] FIGURE 4B is the output eye diagram for the sensor, using a 1 volt peak-to-peak input signal at 1.25 Gbps and a 50 megaHertz (MHz) low pass filter. A 30-50 MHz low pass filter is preferable, since above 50 MHz the response becomes a function of bandwidth. The eye in FIGURE 4B is completely closed, but the peak-to-peak amplitude of the eye is close to the peak-to-peak amplitude of the transmitted signal, even though the sensor bandwidth is less than a tenth of the data rate. FIGURE 4C depicts the same data plotted in FIGURE 4B superimposed with peak detector outputs with an exponential decay at a rate of 100 kilo-Hertz (KHz), a decay rate selected to be much lower than the low frequency content of the input data.~~

~~[0037] FIGURE 4D illustrates results of a parametric simulation varying 1.25 Gbps input data amplitude over four different levels (0.25 V, 0.5V, 0.75 V and 1.0 V) and sensor bandwidth over 16 linear steps (from 7.8125 MHz to 62.5 MHz). The results suggest that the peak-to-peak output of a low frequency sensor is a good representation of the peak-to-peak input signal amplitude. As the sensor~~

~~bandwidth is varied, the peak-to-peak output goes through two fairly linear slopes: at very low sensor bandwidths (less than 1/40th of the data rate), the sensitivity is higher than at higher sensor bandwidth, resulting from roll-off in the spectrum of the input signal. Once the input spectrum begins to fall, signal power in the combined spectrum (both signal and low pass filter) reduces at twice the rate, resulting from roll-off due to the low pass filter nature of the signal and the high pass filter nature of the signal. This roll-off is depicted in FIGURE 4E, where signal LPF-1 (the middle sloped line and the horizontal line connecting that line to the ordinate) covers the signal spectrum such that power rolls off due to a single pole (the low pass filter) as sensor bandwidth is reduced, while signal LPF-2 (bordering the cross-hatched area) covers the signal spectrum such that power rolls off due to two poles (one due to the sensor low pass filter and the other due to the high pass filter of the signal spectrum, depicted by darker lines).~~

[0023] The present invention allows precise control over average power output for a light source in a data transmission system based on power measurements.~~, while~~ Other methods may be employed for estimating and controlling either extinction ratio or optical modulation

amplitude using data obtained from average power values. In one embodiment, the power parameters required for such control may be derived from temperature and forward voltage measurements. ~~In an alternative embodiment, peak-to-peak measurements from a low bandwidth monitor diode directly indicate optical modulation amplitude.~~

[0024] It is important to note that while the present invention has been described in the context of a fully functional system, those skilled in the art will appreciate that at least portions or aspects of the mechanism of the present invention are capable of being distributed in the form of a machine usable medium containing instructions in a variety of forms, and that the present invention applies equally regardless of the particular type of signal bearing medium utilized to actually carry out the distribution. Examples of machine usable mediums include: nonvolatile, hard-coded type mediums such as read only memories (ROMs) or erasable, electrically programmable read only memories (EEPROMs), recordable type mediums such as floppy disks, hard disk drives and compact disc read only memories (CD-ROMs) or digital versatile discs (DVDs), and transmission type mediums such as digital and analog communication links.

[0025] Although the present invention has been described in detail, those skilled in the art will understand that various changes, substitutions, variations, enhancements, nuances, gradations, lesser forms, alterations, revisions, improvements and knock-offs of the invention disclosed herein may be made without departing from the spirit and scope of the invention in its broadest form.

WHAT IS CLAIMED IS:

1. A system comprising:

a controller that, when operably coupled to a light source emitting light at a selectively variable output power, determines an output power for emitted light based upon measurements of one or more of forward voltage and current across the light source, ambient temperature around the light source, and a factor specific to mounting of the light source.

2. The system according to claim 1, wherein the forward voltage is employed to determine a forward current through the light source, and wherein the output power is determined based further upon the forward current.

3. The system according to claim 2, wherein the forward current is measured, calculated or determined from a look-up table.

4. The system according to claim 1, wherein the forward voltage is employed to determine a die temperature for the light source, and wherein the output power is determined based further upon the die temperature.

5. The system according to claim 4, wherein the die temperature is calculated or determined from a look-up table.

6. The system according to claim 1, wherein the output power is determined without measurement of emitted light.

7. An optical subassembly including the system according to claim 1, the optical subassembly further comprising the light source and adapted for transmission of data over an optical transmission medium.

8. A computer including the optical subassembly according to claim 7, the computer further comprising:

a processor coupled to the controller; and

a network connection through the optical subassembly to the optical transmission medium.

9. A method comprising:

determining an output power for light emitted from a light source emitting light at a selectively variable output power, wherein the determination of the output power is based upon measurements of one or more of forward voltage and current across the light source, ambient temperature around the light source, and a factor specific to mounting of the light source.

10. The method according to claim 9, further comprising:

employing the forward voltage to determine a forward current through the light source; and

determining the output power based further upon the forward current.

11. The method according to claim 10, further comprising:

measuring the forward current;

calculating the forward current; or

determining the forward current from a look-up table.

12. The method according to claim 9, further comprising:

employing the forward voltage to determine a die temperature for the light source; and

determining the output power based further upon the die temperature.

13. The method according to claim 12, further comprising:

calculating the die temperature; or

determining the die temperature from a look-up table.

14. The method according to claim 9, further comprising:

determining the output power without measurement of emitted light.

15. An optical subassembly comprising:

a light source emitting light at a selectively variable output power; and

a controller that, when operably coupled to the light source, determines an output power for emitted light based upon measurements of one or more of forward voltage and current across the light source, ambient temperature around the light source, and a factor specific to mounting of the light source.

16. The optical subassembly according to claim 15, further comprising:

a temperature sensor proximate to the light source and coupled to the controller, the temperature sensor providing measurements of the ambient temperature for use by the controller.

17. The optical subassembly according to claim 16, wherein the controller further comprises:

a voltage detector providing measurements of the forward voltage to the controller.

18. The optical subassembly according to claim 17, wherein the forward voltage is employed to determine one or both of a forward current through the light source and a die temperature for the light source, and wherein the output power is determined based further upon one or both of the forward current and the die temperature.

19. The optical subassembly according to claim 18, further comprising:

a memory communicably coupled to the controller, the memory containing one or both of a look-up table for the forward current and a look-up table for the die temperature.

20. The optical subassembly according to claim 19, wherein the output power is determined without measurement of emitted light emitted by the light source.

METHOD OF SENSING VCSEL LIGHT OUTPUT POWER BY MONITORING ELECTRICAL CHARACTERISTICS OF THE VCSEL

ABSTRACT OF THE DISCLOSURE

Output power of light emitted from a data transmission light source is determined based upon forward voltage, forward current, ambient temperature and a factor specific to the manner in which the light source is mounted. Output power is determined with sufficient accuracy to control operation of the data transmission light source for compliance with eye safety and transmission protocol requirements without use of a complex lens and monitor diode.